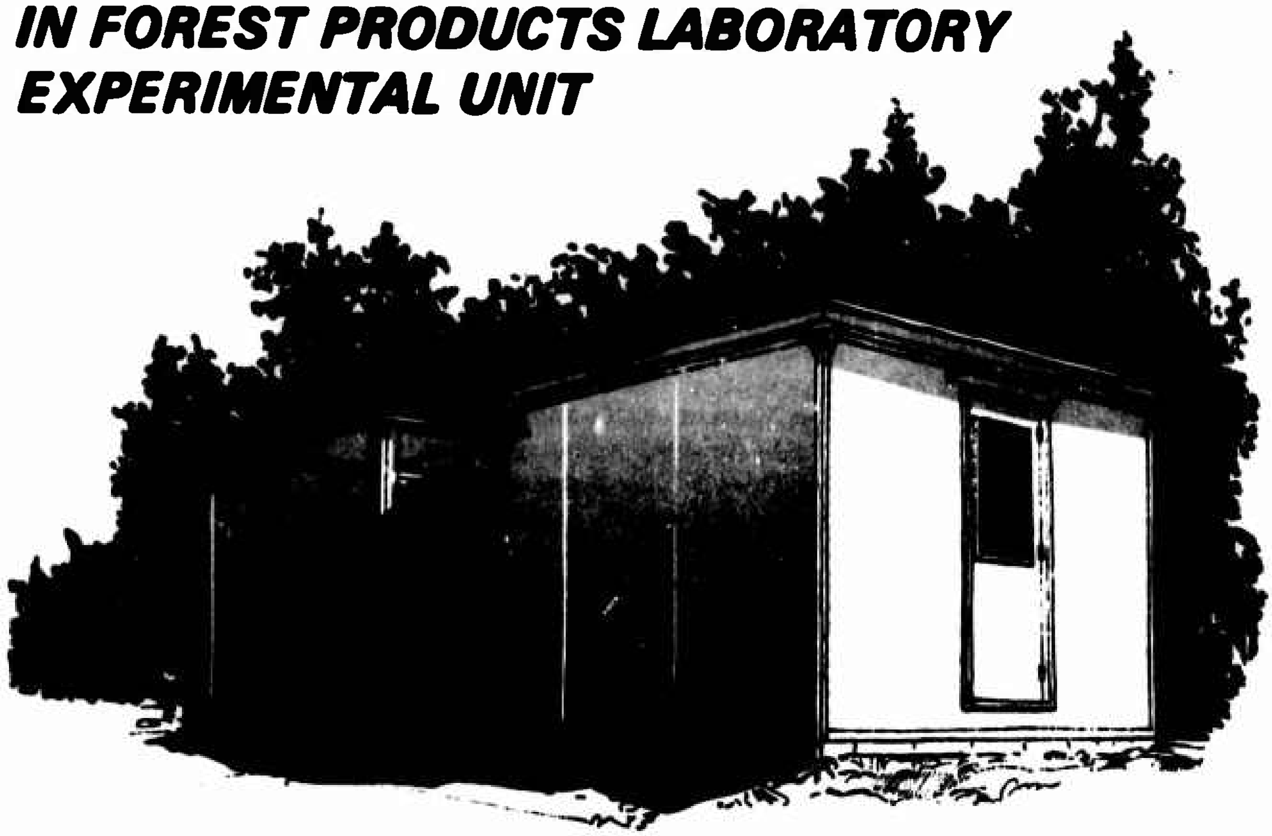
LONGTIME PERFORMANCE OF SANDWICH PANELS IN FOREST PRODUCTS LABORATORY EXPERIMENTAL UNIT



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ABSTRACT

Study of the basic design, fabrication, and construction of structural sandwich materials started at the Forest Products Laboratory in the mid 1940's. It was recognized that, even with this extensive basic research, additional information was needed to establish the serviceability and durability of sandwich construction designed as a building component. Accordingly, an experimental unit was built at the Laboratory in 1947 to provide a facility for longtime exposure tests under conditions simulating those of actual houses.

Performance of selected sandwich panels in the 12- by 38-foot exposure unit was periodically evaluated for various lengths of service up to 21 years. Such panels were constructed of paper honeycomb cores and a variety of facings including plywood, medium-density and high-density hardboard, particleboard, paperboard, cement asbestos, and aluminum. Observations of seasonal bowing of panels were also made over a 15-year period.

After 21 years of exposure, the unit was dismantled and re-erected at a new location. During this move all wall, floor, and roof panels were tested for stiffness and selected panels were tested to failure.

The plywood-faced panels exhibited a minimum of movement due to temperature and moisture changes, and retained a high proportion of original stiffness and strength properties. Other panel constructions were less stable under moisture and temperature changes. Only a few panels had a material loss in stiffness and most panels retained a strength well above the design load.

The new experimental unit, incorporating the better panels and new ones with considerable promise, is continuing to furnish performance data.

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LONGTIME PERFORMANCE OF SANDWICH PANELS IN FOREST PRODUCTS LABORATORY EXPERIMENTAL UNIT

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INTRODUCTION

Structural sandwich is a layered construction comprising a combination of relatively high-strength facing materials intimately bonded to and acting integrally with a low-density core material. Although structural sandwich construction has attained its well-deserved recognition only in recent years, its concept and a vision of its possibilities are not new. An efficient sandwich of metal facings and a plywood core was produced commercially some four decades ago, and no doubt there were applications at even earlier dates. In World War II, one of the most spectacular applications of structural sandwich construction was DeHaviland's mosquito bomber, which employed birch plywood facings with a lightweight balsa wood core.

The possibilities through structural design of utilizing materials more efficiently, the development of prefabrication techniques, and the postwar production and availability of a great variety of facing and core materials, ushered in a new era of structural sandwich construction.[2] One end use where such factors are particularly important is housing.

Application of a new and untried construction to housing naturally raised a great many questions directly related to design, material selection, fabrication methods, strength, and durability. It was also desirable to determine, by some accelerated method, the relative serviceability of the various combinations of facings and cores of the proposed sandwich panels.

The need for basic information on these and related questions led to the development of a continuing research program at the Forest Products Laboratory, extending over a number of years.

Despite the encouraging results of accelerated aging tests, the question remained as to how well these tests could be depended upon to give an accurate indication of longtime serviceability. The most effective and convincing answer would obviously be through a record of actual performance over a long period of time. Therefore, an experimental unit was built at the Laboratory in 1947 to evaluate structural sandwich constructions under conditions simulating those of actual dwellings.

Winter temperature inside the unit was maintained at 65° ± 5° F. and a humidifier was operated to simulate moisture conditions in an occupied house.

Selected panels in the experimental unit were tested for stiffness and strength in 1948, 1955, 1960, 1962, and 1968. During these tests, some panels were cut in half and one-half of a panel

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[1] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[2] A bibliography is provided on page 14 of this research paper.

was destructively tested while the other half was reinstalled in the test unit. Some complete panels were destructively tested and eliminated from the unit. As panels were eliminated, replacement panels embodying new materials and fabrication techniques were installed.

In addition to stiffness and strength tests, measurements of the amount of bow in each panel were made over a period of 15 years. Monthly average values of deformation clearly indicated the behavior of the various panel constructions to seasonal changes in temperature and humidity.

In 1968, the entire experimental unit was disassembled and moved to a new location. During this move, all sandwich panels in the unit were tested for stiffness and selected panels were destructively evaluated.

Then a new experimental unit was erected that contained some of the best performing panels, as well as promising replacement panels. Plans are to expose the new unit for at least 9 more years to furnish data on which to judge sandwich performance in housing.

EXPERIMENTAL UNIT EMPLOYING SANDWICH CONSTRUCTION

The complete experimental unit re-erected in 1968 is shown in figure 1.[3] Overall dimensions of the unit are 32 feet 6 inches long by 12 feet wide by 8 feet high. It is oriented with its longitudinal axis east and west so the experimental wall panels in the long sides are placed to receive the two extremes of exposure. The unit is on a concrete perimeter foundation over a 4-foot crawl space. Three sandwich floor panels are placed in the west room of the unit, and the remainder of the floor is conventional plywood subfloor over 2 by 8 joists spaced 16 inches apart.

The walls rest directly on the sill and fit over a sole plate secured to the sill. The end walls are made up of 4-foot-wide panels. The east end wall panels are of sandwich construction; the west end wall is insulated stressed-skin construction. The center panel at each end contains a door. The north and south walls are made up of experimental sandwich panels of a variety of materials except that a 4-foot-wide panel containing a door is located near the center of the north side, and a similar panel containing a window is placed in the south side opposite the door.

The unit is partitioned 11 feet from the east end and 13 feet from the west end, leaving an 8- by 12-foot utility room near the center (fig. 2). One partition is sandwich construction; the other is uninsulated stressed-skin construction. Partitions are routed on the bottom to seat over a sole plate secured to the floor, and on the ends and top to receive cleats which are glued to the wall and roof panels.

A 1/2-inch space was provided between adjacent side wall panels to permit them to deform without restriction. The space is filled with glass fiber insulation and the joints are taped to provide the desired seal.

A 3/4- by 2-1/2-inch continuous plate, placed in the grooves at the panel tops, ties the panels together at the top. Cleats glued to the roof panels seat in the groove above the continuous plate and the panel facings are fastened to the cleats with screws.

The 1/2-inch space between roof panels is filled with insulation and taped in the same manner as the wall panels. The panels are covered with a metal roof made in 1-1/2- and 2-foot-wide sections. Standing seams where adjacent sections join are covered with a sliding metal cap.

Standard window and door frames are adapted to the 3-inch wall thickness. Rough frames were glued in place when the wall panels were fabricated. A standard double-hung sash is used for the window. Doors are sandwich construction. Exterior doors have type XN cores and two-ply crossbanded birch facings made up of 1/16-inch veneer. One interior door has paper-overlaid 1/8-inch Douglas-fir veneer facings; the other has two-ply Douglas-fir facings.

Details of Panel Construction

The sandwich panels in the experimental unit are primarily constructed of paper honeycomb cores with plywood or other wood-base facings; however, some metal facings are used and some of the panels employ rigid insulation as core material. Details of each panel construction,

[3]The original experimental unit is discussed in the Appendix.

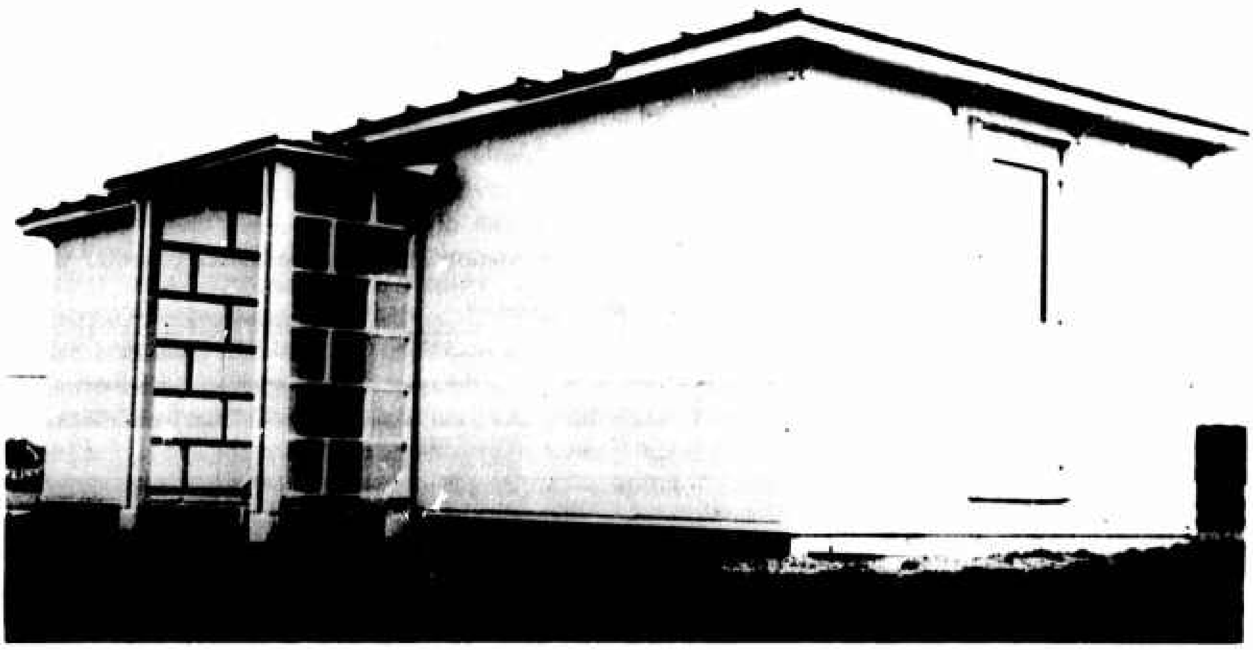

Figure 1.--Sandwich experimental unit as re-erected in 1968.

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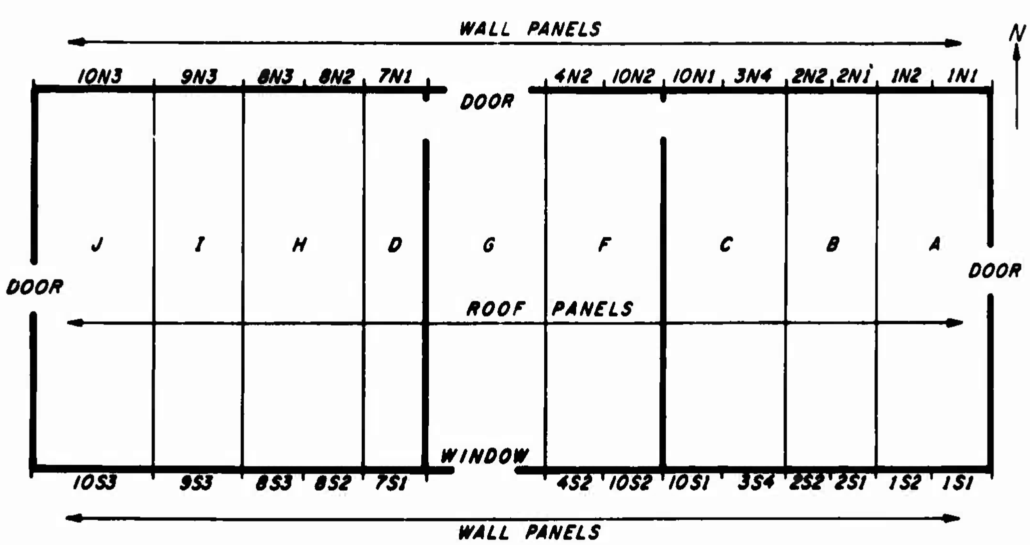

Figure 2.--Positions of numbered wall and roof panels in the sandwich experimental unit (1968). M 138 281

along with year of installation, are given in table 1.

Core materials.--The paper honeycomb cores used were of two types; the expanded or Christmas-bell type, and the corrugated-paper type. Expanded cores may be produced with a variety of honeycomb cell sizes. Variations of the corrugated paper cores are possible by changing orientation of the flute axis with respect to the facings.

The expanded paper core (fig. 3) was produced by assembling sheets of paper flatwise and bonding along continuous narrow bonds at regular intervals across the sheet. Bonds were staggered for adjacent sheets. After sheets were bonded together, they were cut off to the thickness desired for the core. The segments were then expanded to develop the honeycomb pattern. All of the expanded cores except those in the aluminum-faced panels contained 8 or 11 percent of thermosetting phenolic resin.

Corrugated cores were made from a typical kraft paper weighing about 45 pounds per ream (500 sheets 24 by 36 in.), impregnated with about 15 percent of a water-soluble phenolic resin. The corrugated sheets were bonded together with

Table 1.--Properties of wall panels in the experimental sandwich unit

Panel No.	Core type	Facing	Type adhesive and press	Year installed	Stiffness[1]: Before exposure: Deflection	Stiffness[1]: Before exposure: Deflection span ratio	Stiffness[1]: After exposure: Year tested	After exposure: Total exposure	After exposure: Deflection	After exposure: Change	Strength: Before[2] exposure	Strength: After exposure: Year tested[3]	After exposure: Total exposure	After exposure: 96-inch span	After exposure: Change
					In.			Yr.	In.	Pct.	P.s.f.		Yr.	P.s.f.	Pct.
1N1	Corrugated XN	1/4-inch Douglas-fir plywood overlay[4]	Acid-catalyzed phenolic glue; cold press	1947	0.121	1/790	1968	21	0.117	+3	263	1962	15	365	+38
1S1	do.	do.	do.	1947	.125	1/770	1968	21	.117	+6	263	1962	15	367	+38
1N2	Expanded	0.1-inch paperboard[5]	do.	1961	.302	1/320	1968	7	.291	+4	118	1962	1	76	-21
1S2	do.	do.	do.	1961	.306	1/315	1968	7	.281	+8	118	1962	1	101	-15
2N1	do.	0.02-inch aluminum	Phenol vinyl, press not known	1947	.365	1/260	1968	21	.361	+1	200	1962	15	118	-41
2S1	do.	do.	do.	1947	.370	1/260	1968	21	.361	+2	200	1962	15	160	-20
2N2[3]	do.	1/4-inch, 2-layer particleboard with facings of redwood flakes[6]	Acid-catalyzed phenolic glue; cold press	1962	.320	1/300	1968	6	.436	-36	121				
2S2	do.	do.	do.	1962	.306	1/315	1968	6	.422	-38	121				
3N4	do.	1/2-inch medium-density hardboard	do.	1962	.268	1/360	1968	6	.246	+8	123	1968	6	155	+26
3S4	do.	do.	do.	1962	.259	1/370	1968	6	.240	+7	123	1968	6	150	+22
4N2	do.	1/8-inch tempered hardboard	Contact adhesive, nip-roll bonding	1962	.286	1/335	1968	6	.309	-9	109	1968	6	84	-23
4S2	do.	do.	do.	1962	.282	1/340	1968	6	.281	0	109	1968	6	103	-6
7N1	Corrugated XN	0.2-inch two-ply Douglas-fir plywood with overlay	Acid-catalyzed phenolic glue; cold press	1947	.158	1/610	1968	21	.155	+2		1968	21	246	
7S1	do.	do.	do.	1947	.157	1/605	1968	21	.154	+2		1968	21	283	
8N2	do.	1/8-inch high-density hardboard	Phenol resorcinol; hot press	1948	.245	1/390	1968	20	.249	-2	201	1968	20	200	0
8S2	do.	do.	do.	1948	.243	1/395	1968	20	.275	-13	201	1968	20	220	+9
8N3	Expanded	1/4-inch, 2-layer particleboard with facings of Douglas-fir flakes[6]	Phenol resorcinol; cold press	1968	.311	1/309					176				
8S3	do.	do.	do.	1968	.285	1/337					176				
9N3	Expanded with 1-inch urethane foam	1/4-inch plywood with medium density overlay	do.	1968	.112	1/855					247				
9S3	do.	do.	do.	1968	.102	1/940					247				
10N1	Corrugated PN	1/4-inch Douglas-fir plywood	Acid-catalyzed phenolic glue; cold press	1947	.120	1/800	1968	21	.090	+30	251	1962	15	410	+63
10S1	do.	do.	do.	1947	.125	1/770	1968	21	.110	+12	251	1962	15	321	+28
10N2	Expanded	1/4-inch birch plywood (inner face) 1/8-inch aluminum hardboard (outer face)	do.	1962	.226	1/425	1968	6	.223	+1	105				
10S2	do.	do.	do.	1962	.227	1/425	1968	6	.189	+17	105				
10N3	1.9-pound styrofoam	1/4-inch plywood with medium density overlay	Phenol resorcinol; cold press	1968	.150	1/640					323				
10S3	do.	do.	do.	1968	.136	1/710					323				

[1] Based on design load of 20 p.s.f., 96-in. span

[2] Based on test to failure of duplicate panel.

[3] One-half width of panel tested, one-half remaining in place.

[4] Overlay consists of resin-impregnated kraft paper.

[5] Laminated paperboard with 2 films of polyethylene.

[6] Particleboard fabricated with fines (1/4 of total weight) on exposed surface. Phenol resin binder--6 pct. in flakes, 10 pct. in fines.

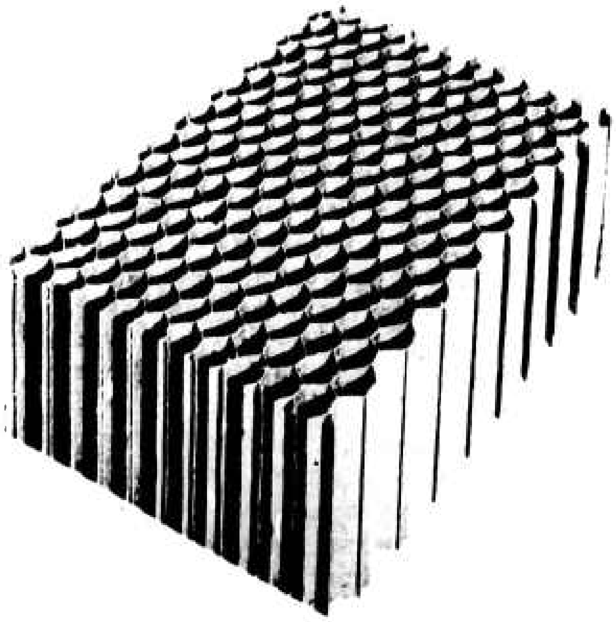

Figure 3.--Expanded hexagonal paper-honeycomb sandwich core.

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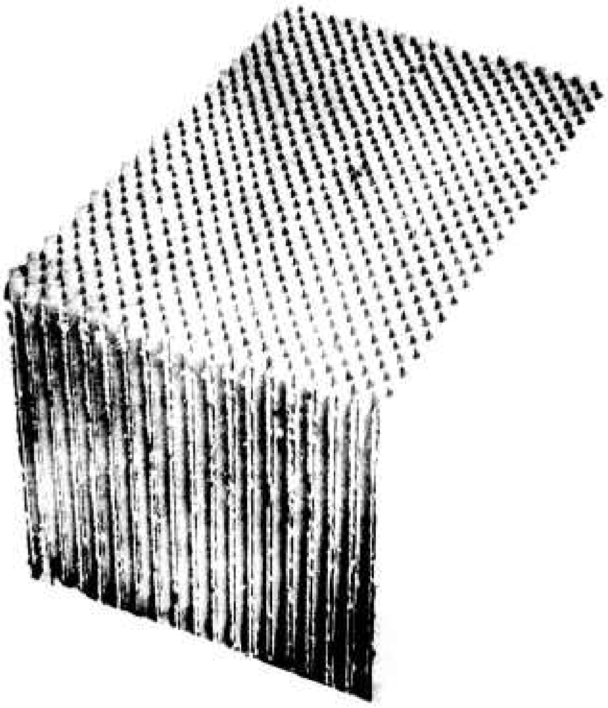

Figure 5.--PN type of corrugated-paper honeycomb core.

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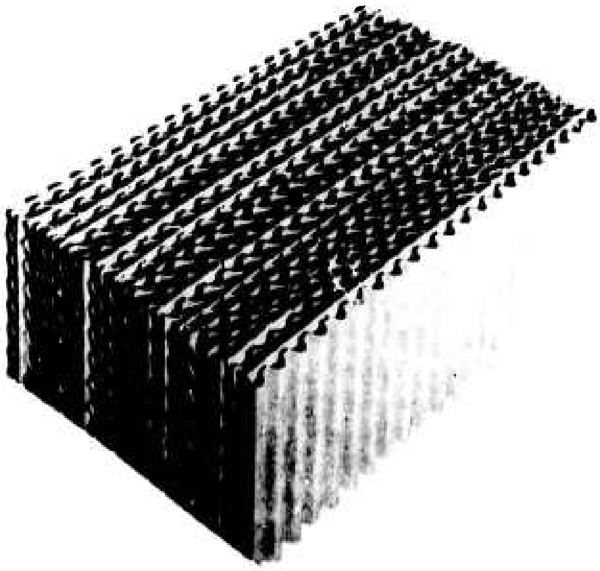

Figure 4.--XN type of corrugated-paper honeycomb core.

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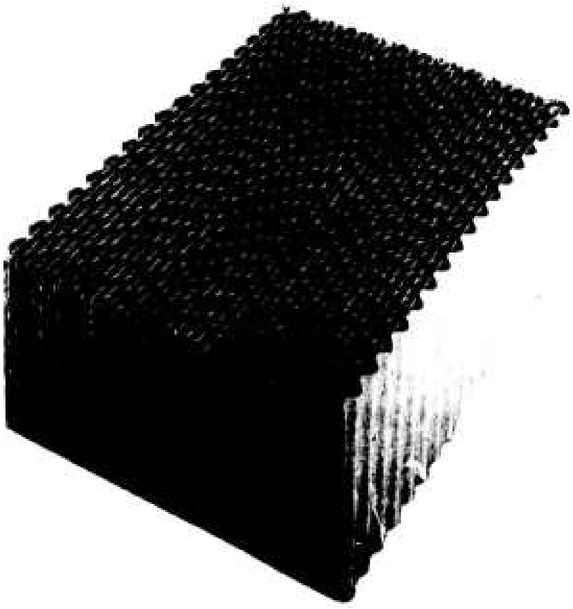

Figure 6.--PNL type of corrugated-paper honeycomb core with flat interleaves between the corrugated sheets.

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an acid-catalyzed phenolic resin.

The core designated XN (fig. 4) was made up of corrugated sheets glued together with corrugations of adjacent sheets at right angles. The assembly was sawed into panel thicknesses and used in a manner that places alternate corrugated sheets with flutes parallel and perpendicular to the facing. Core designated XF was similar except that it was placed in the panel with all flutes parallel to the facings. This orientation results in better insulation, but it is very weak in flatwise compression. A poor glue bond between corrugations could also result in low shear strength.

The core designated PN (fig. 5) was assembled with all flutes parallel. Adjacent sheets were glued together at the nodes. Core designated PNL (fig. 6) was assembled in the same manner except that single-face corrugated board (corrugated board faced on one side with a paper sheet) was used.

In order to make panels suitable for cold climates, two types of rigid insulation are used in the panels fabricated in 1968. One core employs the conventional expanded paper honeycomb with urethane foamed into the cells to a depth of 1 inch (fig. 7). The other core is styrofoam having a density of 1.9 p.c.f. (pounds per cubic foot) (fig. 8).

Facings.--Plywood facings used in the experimental panels are: 1/4-inch, three-ply Douglas-fir of exterior type; 1/4-inch, three-ply Douglas-fir exterior type, with 25 percent phenolic resin-treated paper overlay on one face; two-ply Douglas-fir of 1/10-inch veneers, with the grain of the veneers at right angles and a resin-treated paper overlay on one side; and 3/8-inch, five-ply Douglas-fir, exterior type (for floor panels).

In addition to plywood facings, the experimental unit has panels with several types of wood-base facings and one panel with metal facings. The wood-base facings include medium-density and high-density hardboard, particleboard, and 0.1-inch paperboard with a film of polyethelene under the surface of each side. The metal facing is 0.02-inch aluminum. The only panels of unbalanced construction have 1/4-inch-thick birch plywood inner face and 1/8-inch-thick aluminum-faced hardboard (0.024-inch aluminum with baked enamel finish bonded to 1/16-inch hardboard) outer face.

Walls

All wall panels except the aluminum-faced and paperboard-faced ones are about 3 inches thick. Aluminum-faced panels are 2 inches thick; paperboard-faced panels are 4 inches thick. Wall panels were designed for a wind load of 20 p.s.f. The original panels were made either 2 feet 11-1/2 inches or 3 feet 11-1/2 inches wide to conform to 3- or 4-foot spacing and to allow 1/2-inch clearance for independent bowing of the panels. When structural tests were made, many of the panels were cut in half with one-half destructively tested and the remaining half reinstalled. As a result of these destructive tests, most of the wall panels in the present unit are 1 foot 5-1/2 inches or 1 foot 11-1/2 inches wide. The height of all wall panels is 7 feet 11-1/2 inches. After assembly and curing of the core and facing, panels were trimmed to the appropriate size, and the core was routed from both top and bottom edges to a depth of 1-3/4 inches. Sole plates and top plates seat into grooves formed by routing, and the facings were secured to the plates with screws.

Roof

Roof panels are 14 feet long, spanning the width of the structure with 9-inch overhangs. Two panels, 2 feet 11-1/2 inches wide by 3 inches thick, with aluminum facings were designed for a load of 15 p.s.f. All other roof panels have plywood facings and, except for one panel cut in half for destructive testing, are 3 feet 11-1/2 inches wide by 4-1/2 inches thick. The plywood-faced panels were designed for a load of 25 p.s.f. Three of the original panels were ventilated with 2- by 3-inch ventilating flues spaced 6 inches apart and extending lengthwise through the panels. Cleats glued to the underside of the roof panels near each end seat into grooves at the top of the wall panels and are connected to the wall panels with screws through the wall panel facings.

Floors

The experimental unit has three sandwich floor panels 3 feet 8-1/2 inches wide by 12 feet long

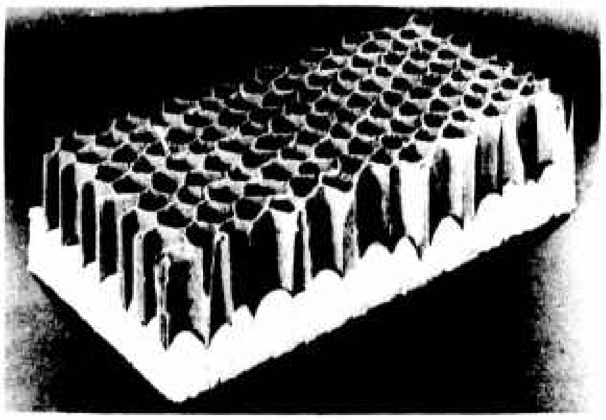

Figure 7.--Expanded hexagonal paper-honeycomb core with 1-inch urethane foam from one side.

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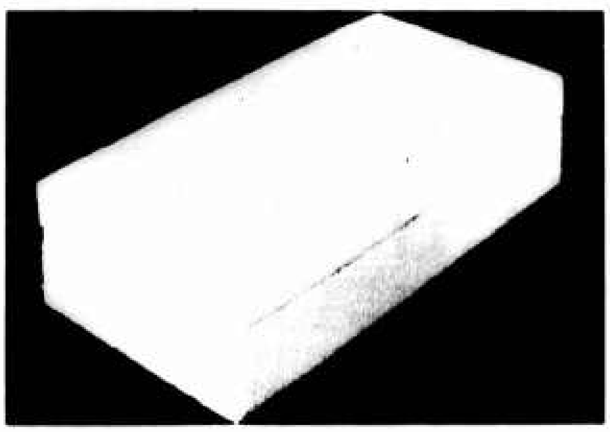

Figure 8.--Styrofoam core with density of 1.9 pounds per cubic foot.

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and 6 inches thick. They were designed for a load of 40 p.s.f. The cores were routed to a depth of 1-1/8 inches on the longitudinal edges to accommodate an insulated spline which connects adjacent panels together. During fabrication of the panels in 1947, a radiant heating system was incorporated by crushing copper hot water heating pipes into the paper core just below the top facing. Although the copper tubing remains in the three floor panels, the remainder of the radiant heating system was not installed in the existing unit. The unit is heated by electric space heaters.

STRUCTURAL TESTS

Panels in the experimental unit have been exposed for varying lengths of time up to 21 years. All panels were tested for stiffness at the time they were fabricated. In addition prototypes of all wall and floor panels were destructively tested. These tests serve as controls for tests to be made after exposure. When the experimental unit was moved in 1968, all panels were again tested for stiffness. Some panels had previously been cut in half with half the panel destructively tested. New panels installed in 1968 were tested only for control values. Tests after exposure will be made at future dates within the next 9 years. Tests of sandwich panel construction prior to erection of initial experimental unit are discussed in the Appendix.

Bending and Stiffness

Tables 1 and 2 give the results of bending and stiffness tests of panels in the experimental unit and bending tests of prototype panels destructively tested at the time the experimental panels were installed. Data on panels not retained in the experimental unit are given in the Appendix. Design loads for the panels were 20 p.s.f. for walls, 25 p.s.f. for the roof, and 40 p.s.f. for the floor. Tests were made by supporting the panel on rollers near the ends and applying load at the quarter points (fig. 9) at a rate of 0.041 inch per minute. Spans for the tests were 90 inches for the wall panels, 133 inches for floor panels, and 147 inches for roof panels. Values shown in the tables are equivalent uniform loads over the unsupported length of the panel.

Wall panels.--Most of the wall panels had a slight increase in stiffness after exposure. The only panels decreasing in stiffness were those with facings of high-density hardboard and redwood-faced particleboard. The hardboard-faced panels had a decrease in stiffness of 0 to 9 percent after 6 years, and a decrease of 2 to 13 percent after 20 years. The particleboard-faced panels had a decrease in stiffness of 36 to 38 percent after 6 years. Even with this decrease in stiffness, the deflection-span ratio for high-density hardboard-faced panels was well above

Table 2.--Properties of roof and floor panels in the experimental sandwich unit

Panel	Core type	Facing[1]	Construction	Thickness	Stiffness[2]: Before exposure: Deflection	Stiffness[2]: Before exposure: Deflection span ratio	Stiffness[2]: After exposure: Year tested	Stiffness[2]: After exposure: Total exposure	Stiffness[2]: After exposure: Deflection	Stiffness[2]: After exposure: Change	Strength: Before[3] exposure	Strength: After exposure: Year tested	Strength: After exposure: Total exposure	Strength: After exposure: 144-inch span	Strength: After exposure: Change
				In.	In.			Yr.	In.	Pct.	P.s.f.		Yr.	P.s.f.	Pct.
						ROOF PANELS									
A	Corrugated XP	1/4-inch, 3-ply plywood	Unventilated	4-1/2	0.440	1/328	1968	21	0.433	+2					
B	Expanded	0.02-inch aluminum	do.	3	[4]1.085	1/133	1968	21	1.110	-2	51				
C	Corrugated XN	1/4-inch, 3-ply plywood	Ventilated	4-1/2	.369	1/390	1968	21	.343	+7					
D	do.	do.	Unventilated	4-1/2	.361	1/399	1968	21	.357	+1		1968	21	174	
F	do.	do.	do.	4-1/2	.336	1/426	1968	21	.337	0					
G	do.	1/4-inch, 3-ply plywood with resin-treated paper on outside of each facing	Ventilated	4-1/2	.305	1/472	1968	21	.309	-1					
H	do.	do.	Unventilated	4-1/2	.339	1/425	1968	21	.320	+6					
I	Expanded	0.02-inch aluminum	do.	3	[4]1.123	1/128	1968	21	1.125	0					
J	Corrugated FN	1/4-inch, 3-ply plywood	do.	4-1/2	.374	1/385	1968	21	.369	+1					
						FLOOR PANELS									
1	Corrugated XN	3/8-inch, 5-ply plywood	Pressed-in hot water tubing	6	[5].297	1/485	1968	21	.230	+23	376				
2	do.	do.	do.	6	[5].297	1/485	1968	21	.243	+18	376				
3	do.	do.	do.	6	[5].297	1/485	1968	21	.230	+23	376				

[1]Both facings of each panel were the same. All plywood was Douglas-fir.

[2]Deflection at design loads of 25 p.s.f. on roof panels, 40 p.s.f. on floor panels.

[3]Test of prototype panels of the construction indicated.

[4]Aluminum-faced panels were designed for 15-lb. load per sq. ft.

[5]Average for the 4 floor panels.

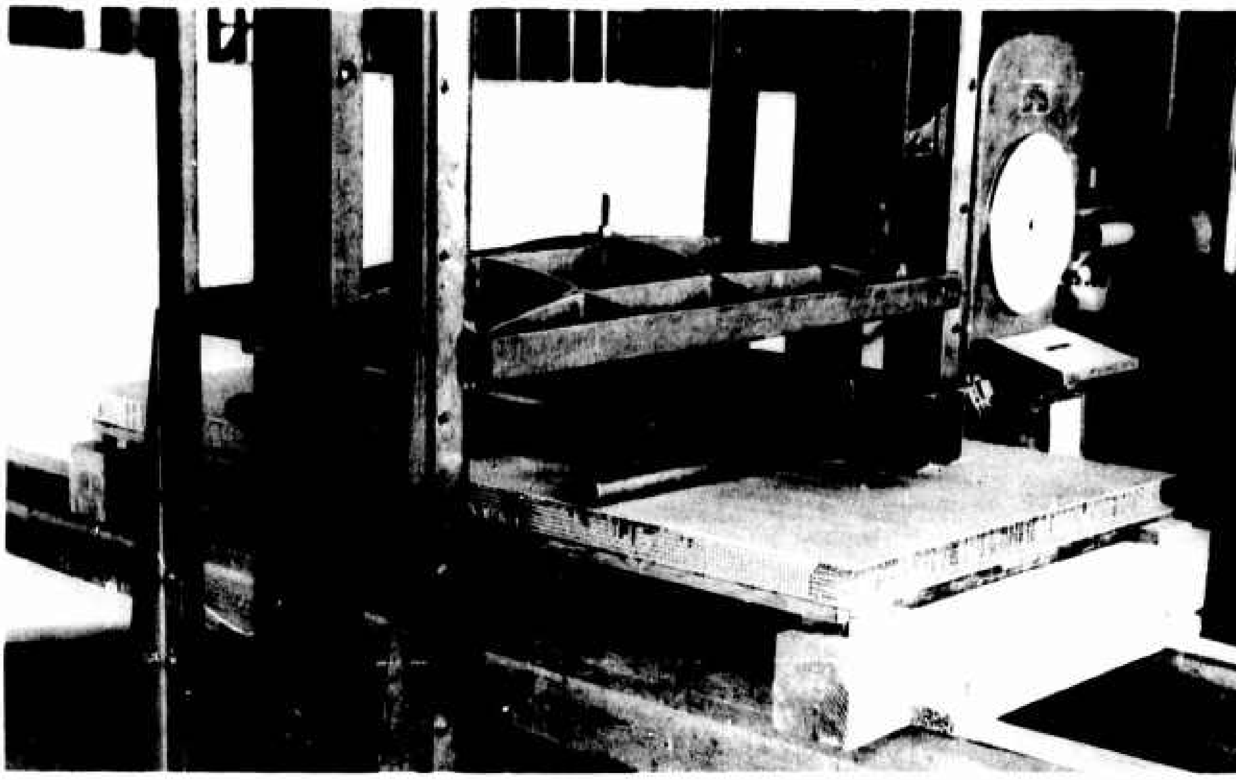

Figure 9.--Method of testing sandwich wall panel with bending load applied at quarter points of span.
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1/270; however, the deflection-span ratio of the particleboard-faced panels decreased below 1/270.

The greatest decrease in strength occurred in the aluminum-faced panels which lost 20 to 41 percent of their strength after 15 years of exposure. Even with this loss, the strength was still about six times the design load of 20 p.s.f. There was also some decrease in strength in panels faced with paperboard and high-density hardboard.

Roof panels.--The change in stiffness was insignificant in all of the roof panels ranging from a 2 percent decrease to a 7 percent increase. There were no strength tests before exposure for comparison with strength after exposure. Only two panels, one ventilated and one unventilated, were tested to failure. There was some concern when panels were first fabricated that moisture might condense within a panel and result in a reduction of panel performance. For this reason some roof panels were built with ventilating ducts. The unventilated panel (fig. 10) showed no loss of strength over the ventilated panel (fig. 11). These tests plus examination of panels indicate that ventilating the roof panels was not necessary for the type of construction used in the experimental panels.

Floor panels.--All of the floor panels showed an increase in stiffness after 21 years of service. The increase ranged from 17 to 23 percent. The panel tested to failure (fig. 12) showed a 16 percent decrease in strength compared to a prototype floor panel tested at the time the experimental panels were put into service. Examination of the panel in the area where the copper tubing was inserted for radiant heat showed no deterioration of the core material or the glue bond between core and facing.

Tension

To assess bond performance flatwise, tension tests were made of specimens taken from several types of sandwich panels that had been exposed for 1 year and for 15 years. The following is a summary of the results of these tests.

1. Plywood-faced panels.--These panels had been exposed for 15 years and consisted of 1/4-

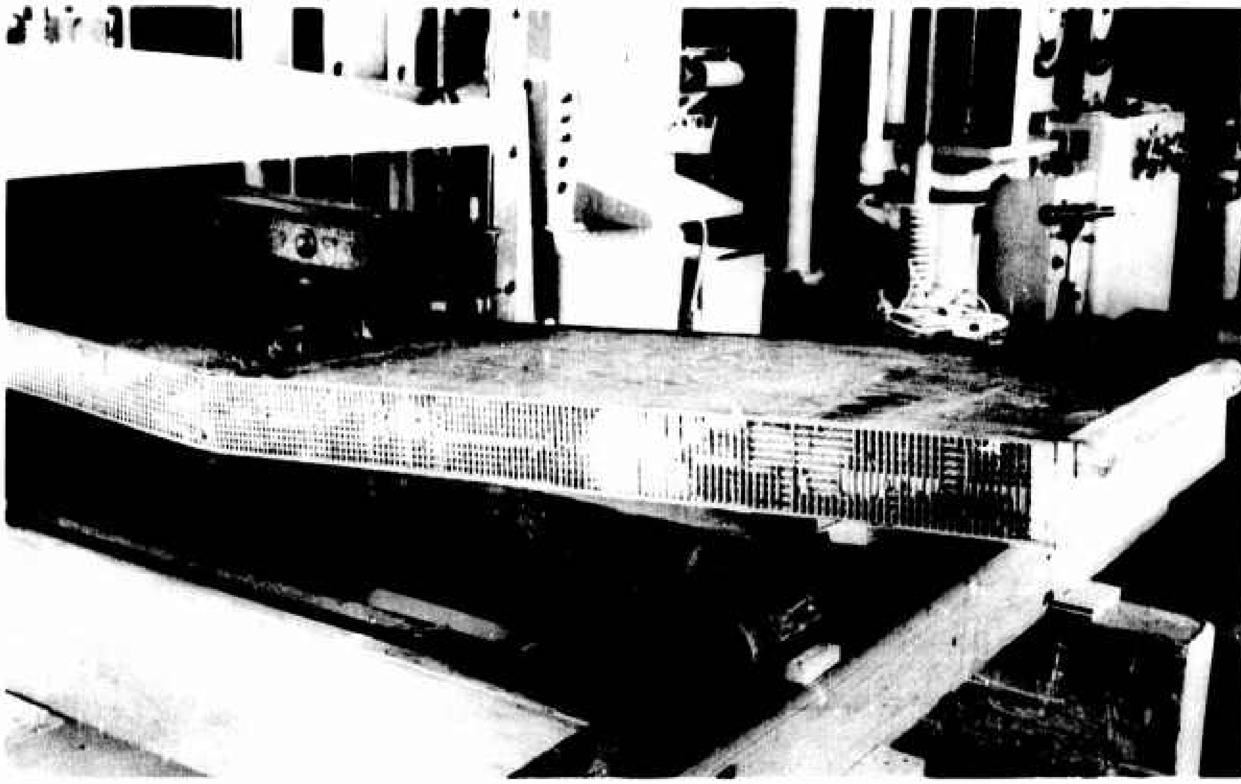

Figure 10.--Final failure of unventilated roof panel after 21 years' exposure.

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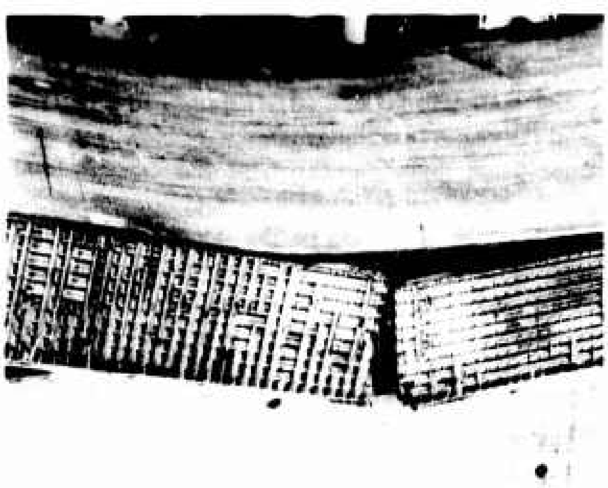

Figure 11.--Final failure of ventilated roof panel after 21 years' exposure.

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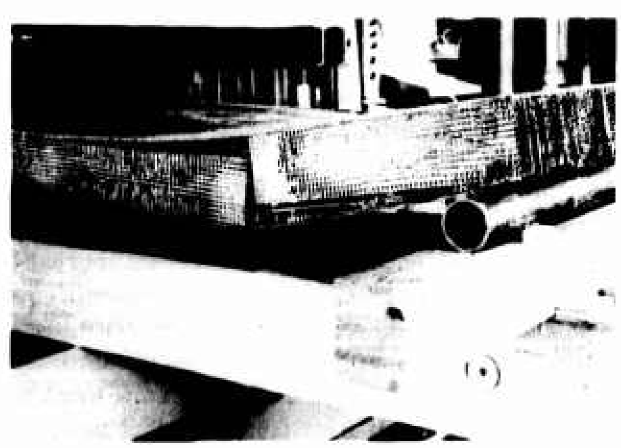


Figure 12.--Final failure of floor panel after 21 years' exposure.

M 134 880

inch Douglas-fir plywood with type XN corrugated paper cores. The average load at failure was slightly over 60 p.s.i. (pounds per square inch), and there was no significant difference between north and south panels. The majority of the failures occurred in the core itself, only a small percentage occurring in the glueline.

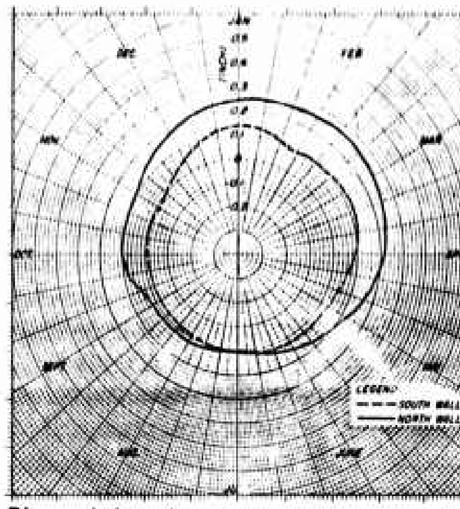
2. Aluminum-faced panels.--These panels were tested after 15 years of exposure and consisted of 0.02-inch-thick aluminum facings and expanded paper core. The average values at failure were quite high; 175 p.s.i. for the north panel and 140 p.s.i. for the south panel. The difference was probably due to the better glue bond of the north panel specimens. The paper thickness of the core of the north panel was 0.012 inch, and 0.006 inch for the core used in the south panel. The greatest percentage of the failures was in the glueline.

3. Paperboard-faced panels.--These panels consisted of 0.10-inch paperboard covers and expanded paper cores. Exposure period was 1 year. The average tension values were quite low (16 p.s.i.), and there was little difference between the north and south panels. Most of the failures occurred in the facings and few, if any, in the glueline.

BOWING OF WALL AND ROOF PANELS

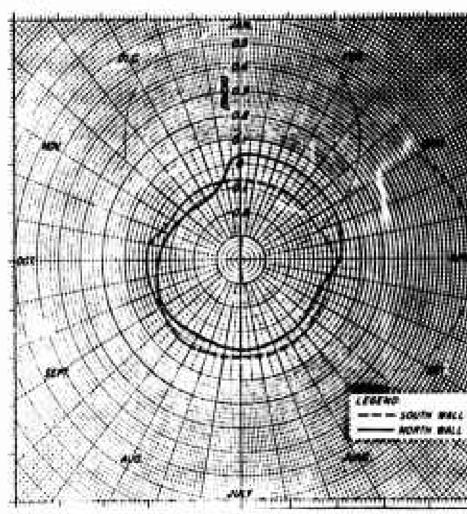
Bowing of wall and roof panels due to moisture and temperature effects was studied over a 15-year period for the original panels and over a 4-year period for replacement panels installed in 1962. Observations showed a cyclic pattern with panels generally having about the same seasonal bow year after year.

Plywood-faced panels were essentially flat during the warmest part of the year, bowing outward during the cold season with the north panels bowing more than the south panels (fig. 13). The south panels remained almost flat for the 6-month period from May to November and bowed outward to a maximum of a little more than 1/10 inch during the coldest season. The north panels were



Plywood faced

M 126 267



Aluminum faced

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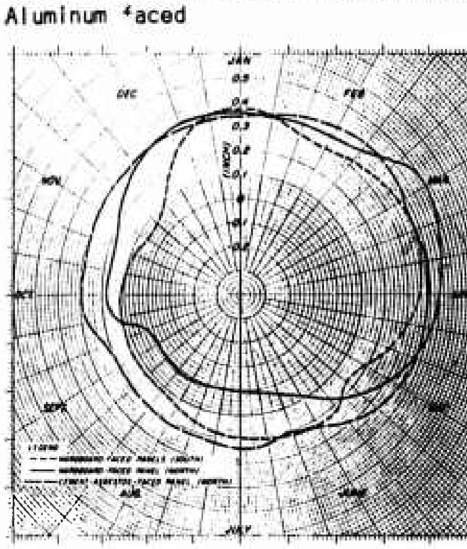


High-density hardboard faced and cement-asbestos faced

M 126 269

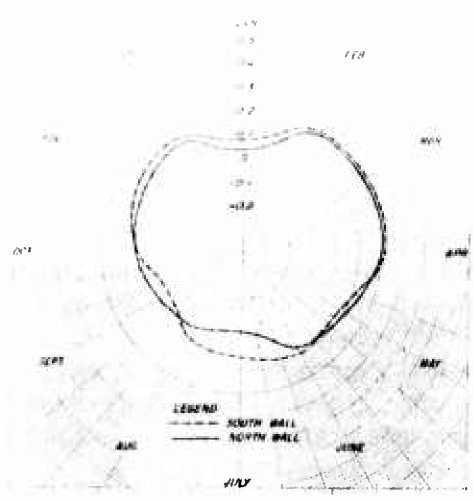
Figure 13.--Average bow of sandwich wall panels by months during exposure from August 1947 to June 1962.

flat only in July and bowed outward to a maximum of about 1/4 inch in February.

Aluminum-faced panels 2 inches thick on the south side were nearly flat from April to October but had an inward bow of slightly less than 1/10 inch during the winter (fig. 13). The north panels bowed slightly inward during all months except from January to April when there was a slight outward bow.

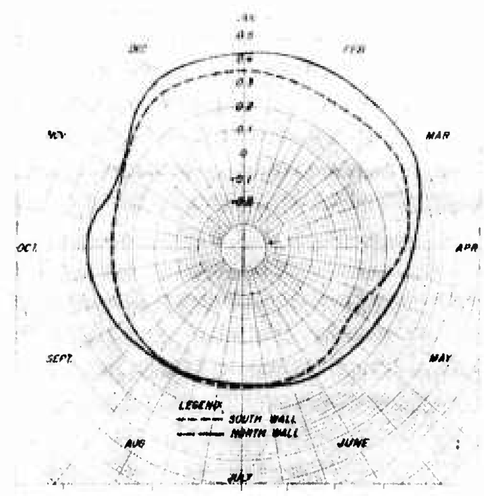
Average seasonal bowing curves of panels faced with high-density hardboard and with cement-asbestos are also shown in figure 13. The hardboard-faced panels on the north had the largest bow, ranging from a flat condition in July and August to an outward bow of almost 1/2 inch in March. The range of bow in the south exposure hardboard-faced panels was from an outward bow of 1/10 inch in summer to almost 4/10 inch in winter. The cement-asbestos panel was somewhat more stable with a variation of only about 2/10 inch between summer and winter conditions.

The average seasonal bowing of paperboard-faced panels (4 inches thick) is shown in figure 14. Bowing of these panels was influenced primarily



Paperboard-faced panels

M 138 282



Particleboard-faced panels

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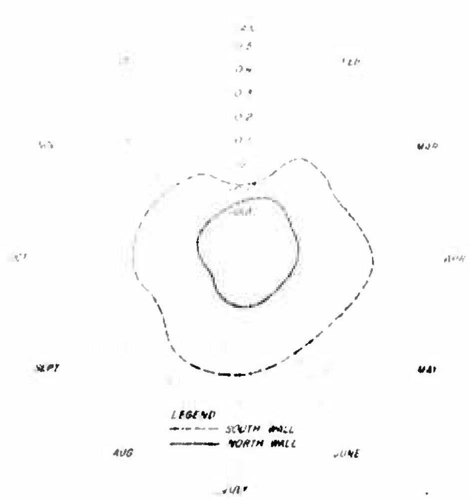
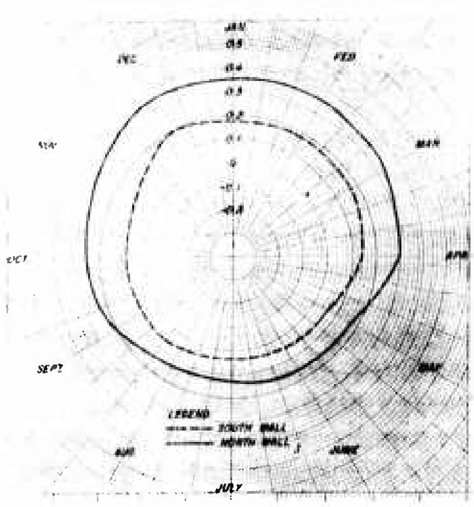


Medium-density-hardboard-faced panels

M 138 285



Plywood inside, aluminum-faced hardboard outside

M 138 283

Figure 14.--Average bow of sandwich wall panels by months during exposure at FPL from January 1963 to June 1966.

by moisture content of the faces with the largest outward bow in March and a slight inward bow in September. Bow of the panel in the north wall was generally slightly less than bow of the panel in the south wall. The maximum outward bow was slightly over 2/10 inch, and the maximum inward bow was less than 1/10 inch.

The particleboard-faced panel in the north wall bowed outward from a maximum of almost 1/2 inch in the middle of winter to a minimum of slightly less than 2/10 inch in the summer (fig. 14). The north and south panels were bowed nearly the same amount in summer, but the panel on the north side was bowed about 1/10 inch more than the panel on the south side during winter.

Average bow of the medium-density-hardboard-faced panels (fig. 14) on the north side ranged from slightly less than 4/10 inch outward in the winter to about 1/10 inch outward in the summer. Average bow of the panel on the south side was from about 2/10 inch outward in the winter to almost flat in the summer.

The only panel of unbalanced construction had a 1/4-inch birch plywood inside facing and a 1/8-inch aluminum-faced hardboard outside facing. The north panel had a maximum inward bow of about 1/4 inch in August and an inward bow of about 1/10 inch in February (fig. 14). Bow in the south panel ranged from about 1/10 inch inward in January to about 2/10 inch outward in April.

Average bowing of plywood-faced and aluminum-faced roof panels is shown in figure 15. Bowing of the plywood-faced panels ranged from about 1/10 inch inward during the summer to an outward bow of about 1/3 inch during the coldest months. The bowing of aluminum-faced panels ranged from almost flat during the heating season to about 1/10 inch outward during the summer months.

Bowing of the panels with wood-base facing was caused mostly by the difference in moisture content. Calculations indicate a difference in moisture content between inside and outside facings of about 8 percent. This difference reached a maximum near the end of winter due to the lower temperature and consequent higher relative humidity on the outside during the winter. Thermal contraction of the outer facing tended to reduce the amount of bow.

Bowing of aluminum-faced panels was caused by temperature difference in the inner and outer face. This bowing was lessened by the significant

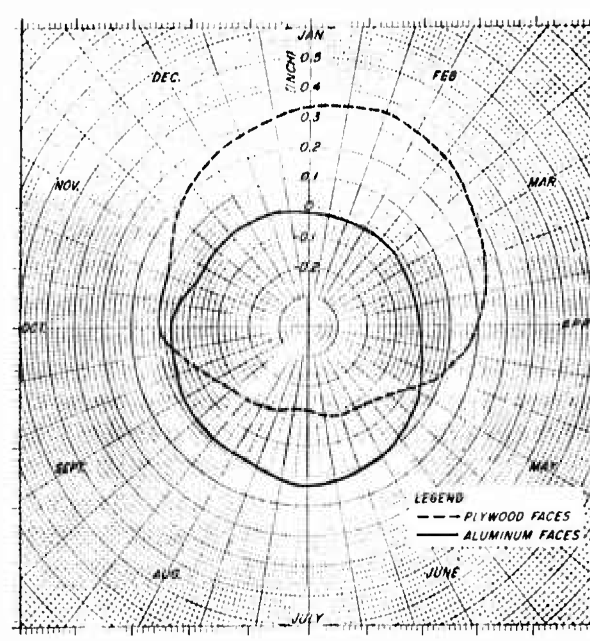


Figure 15.--Average bow of roof panels of plywood-faced and aluminum-faced sandwich by months during exposure from August 1947 to June 1962.

M 126 270

heat loss through the uninsulated panels. If the panels were insulated for a lower U value, there would be a greater temperature differential between inner and outer facings and, consequently, much greater bowing.

Theoretical analysis shows the bow to be proportional to the square of the length and inversely proportional to the thickness. Longer panels applied horizontally would have much greater bow than those in the experimental unit; however, this bow could be largely restrained by suitable fastenings at midlength or by other structural elements, such as partitions. The amount of bow in all the test panels did not produce an objectionable appearance where adjacent panels bowed the same direction and the same amount. There was evidence of bowing where a wall panel intersected a roof panel or a partition, but in practice this would be covered with a molding which conceals most of the movement.

SUMMARY OF OBSERVATIONS

Performance of sandwich panels in the experimental unit over 21 years indicates that panels of nominal thicknesses and constructions can be satisfactorily used for housing construction. Minimum stiffness and strength requirements are easily achieved, and most constructions retain their stiffness and strength properties even after longtime exposure.

Adhesive bonding techniques proved to be adequate with good bonds even after as much as 21 years of service. No moisture problems at the bond were observed. Synthetic resins in the honeycomb material also afford a degree of moisture resistance that insures adequate strength and stability even if the material is immersed.

Plywood-faced panels have demonstrated excellent performance during 21 years of service. They had a minimum of movement due to temperature and moisture changes, and retained stiffness and strength. Mechanical fasteners used in assembling a house might govern the thickness of facings. In some cases, thinner prefinished plywood with a nonmarring plastic surface might be used for the interior facing.

Although plywood was relatively stable, the other wood-base facings were more affected by moisture and temperature changes. In normal construction, much of the bowing would be eliminated by fastenings; however, restricting the panel edges might result in cross bowing or cupping. Therefore, facings that are highly sensitive to temperature and moisture changes are undesirable.

The feasibility of radiant heating coils in sandwich floor panels was demonstrated in the original experiment unit. The coils did not cause any deterioration in the core material or the bond between core and facing.

Minimum insulation requirements for many areas of the United States are satisfied by the corrugated core; however, this core does not provide adequate insulation for the colder climates. Expanded core provides even less insulation. The panels with styrofoam core or urethane foamed into expanded core both have insulating properties comparable to conventional wood-frame house construction with 2 inches of blanket insulation.

The long-term durability test with panels exposed for periods as long as 21 years has shown the feasibility of using this type of construction in housing. The requirements for satisfactory sandwich panels are selection of proper combinations of facings, core, and adhesives; careful fabrication techniques; and good quality control.

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APPENDIX

Initial Sandwich Experimental Unit

The complete experimental unit erected in 1947 is shown in figure 16. Overall dimensions were 38 feet 6 inches long by 12 feet 6 inches wide by 8 feet high. The front of the unit faced north, and both the front and the rear walls were constructed of 10 sandwich panels, generally installed in matched pairs as shown in figure 17. The roof consisted of 10 sandwich panels. Four of the wall panels and two of the roof panels had aluminum facings, and all others had plywood or other wood-base material facings. Both the east and west end walls consisted of three panels. Those on the east were of sandwich construction and those on the west were of stressed-skin construction. One of the panels in each end wall and in the south wall contained a window.

The interior was divided into two 12- by 15-foot rooms and one 8- by 12-foot utility room, with an exterior door, located in the north wall, opening directly into the utility room. Another special feature of the construction was the use of

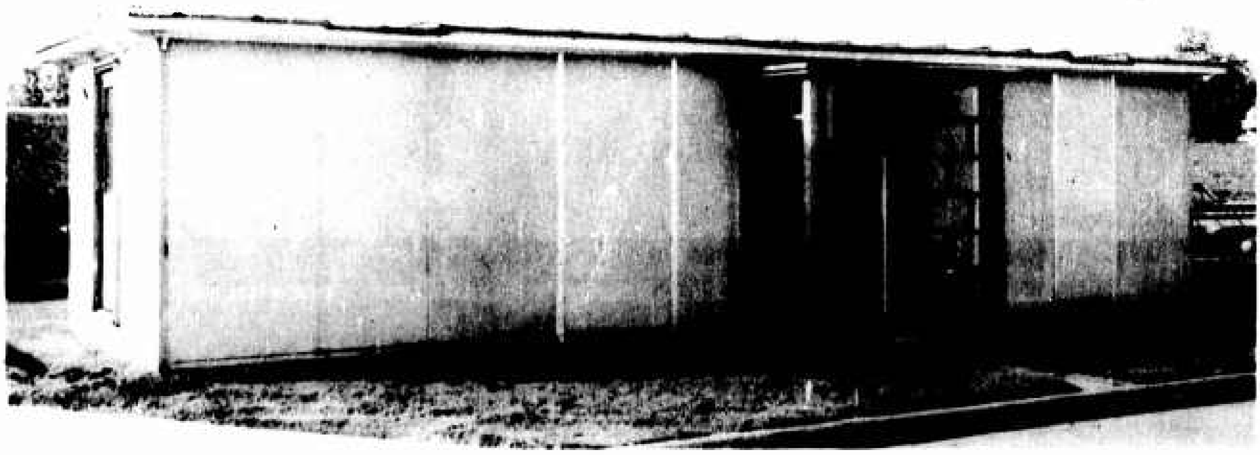

Figure 16.--Original Forest Products Laboratory sandwich experimental unit. M 116 396

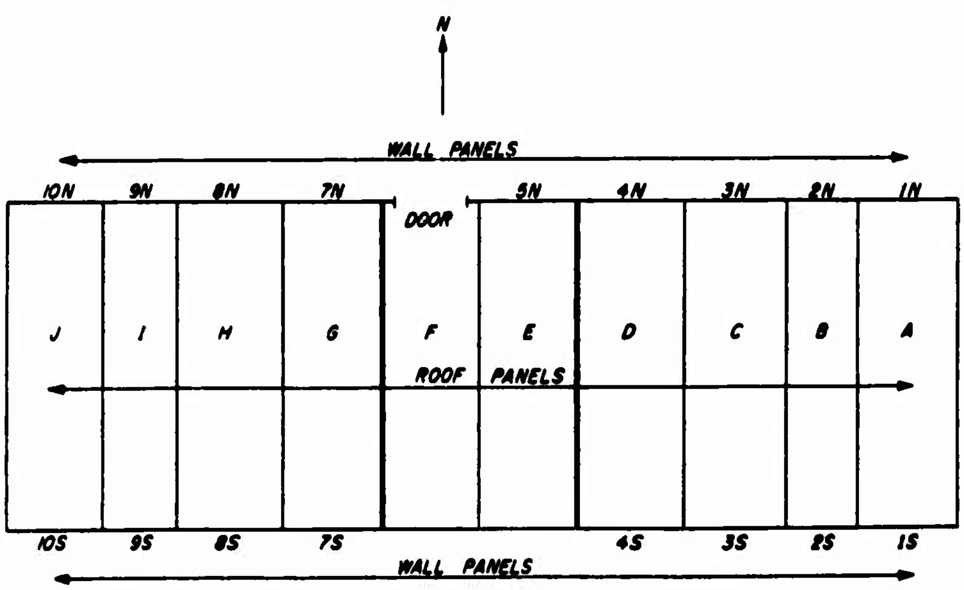

Figure 17.--Positions of original numbered wall and roof panels in sandwich experimental unit. M 126 174

sandwich panels over a crawl space for the floor of the east room, with copper heating pipes installed in the panels during fabrication to determine the effect of radiant heating with hot water on the long-range performance. The west room had a concrete subfloor with radiant heating to permit study of wood finish floors under such heating conditions.

Tests of Panels in the Initial Experimental Unit

Prior to construction of the experimental unit in 1947, small sections of various sandwich constructions were submitted to a variety of tests. Impact bending tests were also made on prototypes for a plywood-faced wall panel, an aluminum-faced wall panel, a plywood-faced floor panel, and an aluminum-faced roof panel. A prototype of each experimental panel was tested to failure in bending, and each experimental panel was tested for stiffness before being installed in the experimental unit. Results of initial strength and stiffness tests for panels are given in tables 1, 2, and 7.

Tension Tests

Flatwise tension tests were made of small sections of sandwich panels to determine the type of failure that might occur in the facing, glueline, or paper core after exposure. ASTM procedure C 297, "Tension Test of Flat Sandwich Construction in Flatwise Plane," was used for these tests. Small 2- by 2-inch-square sections of the exposed sandwich panels were glued to steel plates. After conditioning, a tension load was applied to the steel plates until failure of the specimen occurred. Both plywood- and aluminum-faced specimens had average maximum loads greater than 50 p.s.i.

Accelerated Durability Tests

Paper honeycomb cores.--Prior to the selection of core for the exposure panels, some 72 types of treated paper honeycomb cores were subjected to ASTM procedure C 481, "Laboratory Aging of Sandwich Constructions." A few representative results of the subsequent tests are listed in table 3. General results indicated that strength

Table 3.--Effect of aging on paper-honeycomb sandwich cores[1]

Treating resin: Type	Treating resin: Amount	Ratio of property after aging to property before aging[2] — Compression parallel to flutes: Static strength	Impact strength	Modulus of elasticity
	Pct.	Pct.	Pct.	Pct.
Water-soluble phenolic	20	79	125	107
do.	35	81	80	86
Alcohol-soluble phenolic	20	80	100	70
do.	35	110	100	60
Polyester	20	64	86	223
do.	35	100	70	70

[1] Weight of paper was 90 lbs. per 3,000 sq. ft.

[2] Accelerated aging consisting of 6 cycles of the following: Immersion in water at 120° F. for 1 hour; spraying with wet steam at 200° F. for 3 hours; storage at 10° F. for 20 hours; heating in dry air at 210° F. for 3 hours; spraying with wet steam at 200° F. for 3 hours; and heating in dry air at 210° F. for 18 hours.

and stiffness were reduced about 20 percent and shock resistance very little.

Sandwich panels.--Small sandwich panel specimens with cores and wood facings similar to the original panels in the FPL experimental unit were subjected to ASTM aging procedure C 481 and tested in bending. Generally, the reduction of shear stress in the cores of the aged specimens was about 20 to 30 percent. The reduction in stiffness was about 20 percent, and no visual defects or warping were observed in the aged specimens.

Small specimens of a commercially manufactured 2-inch sandwich with resin-treated paper honeycomb core and aluminum faces were tested in tension perpendicular to the faces after a variety of aging exposures. The exposures and the results of the tests are summarized in table 4. The tests showed that appreciable softening occurred in the adhesive bonding of the core to the facings when exposed to a temperature of 180° F. The adhesive bond also was seriously affected when soaked in water for 48 hours. Exposure to high humidity or to cyclic conditions had less severe effects.

Moisture and Temperature Effects

Moisture and temperature are important factors that may affect the structural properties of sandwiches made of wood or wood-base materials. They may have an immediate effect on the facings or the core, and they are major factors in producing aging effects on facings, core, or adhesive bond.

Facings of wood or wood-base material are hygroscopic; that is, they take on or give off water vapor until they are in equilibrium with the surrounding atmosphere. With an increase of moisture, the dimensions are increased, while structural properties are generally reduced. This can and often does happen to a building. Since the properties of sandwich constructions are largely controlled by the facings, these effects are important. Table 5 gives the structural properties of a number of common facing materials, both wet and dry.

Table 5 also shows the moisture effects, both on dimensions and on strength and stiffness of a number of facing materials. Plywood expands by 0.1 to 0.2 percent of its original length and loses about 18 percent of its strength and stiffness when soaked. Shock resistance is little affected. Hardboards and insulating boards have more expansion than plywood. The reductions of strength and stiffness follow the same order.

Moisture also affects the strength of the paper core. Honeycomb cores A and B in table 6 were tested for compressive and shear strength when dry and when wet. The wet values were about 30 percent in compression and about 45 percent in shear, compared to the dry values given in table 6.

Temperature effects on strength are generally not important in structural sandwich for building construction. The strength of most wood materials increases or decreases only 0.33 to 0.50 percent from that at 70° F. for each degree of temperature change. Adhesives that become plastic at high temperatures should be used with care where there is a possibility of high temperatures in service. On the other hand, thermosetting adhesives that have not been fully cured may become hardened and strengthened by exposure to high temperature. This was shown in tests of sandwich specimens with phenol resin-treated paper honeycomb cores bonded to aluminum facings with the phenol-vinyl resin adhesive.

The effect of severe temperature differences was shown by previous laboratory tests on six sandwich panels 20 by 72 by 3 inches in size. The core was paper honeycomb, and the facings were various combinations of Douglas-fir veneers and plywood, mostly with paper overlay and one with aluminum paint on the warm side. The panels were built into a wall between two rooms, one at 70° F. and the other a refrigerated room at -20° F. Bowing due to temperature occurred immediately; it was toward the warm side and was observed to range from practically nothing up to 0.06 inch in the various panels. With continuing exposure, the bow was reduced because of expansion in the facings on the cold side due to absorption of moisture.

Tests of smaller panels placed near the floor in the same wall showed about 5 percent of moisture in the facing on the warm side, 4 percent in the core, 5 percent in the facing on the cold side, and an additional 5 percent as frost crystals on the inner surface of the cold facing. Bow of the panels was not measured.

Table 4.--Average results of tension tests on specimens of sandwich wall panels[1]

Reference No.	Description	Total time before testing: Weeks	Days	Cycles	Test results[2]: Tensile strength	Location of failure: In glue	In paper
		Weeks	Days	Cycles	P.s.i.	Pct.	Pct.
1	Conditioned at 80° F. and 65 percent relative humidity. Tested dry.				75	58	42
2	48 hours in water at 80° F. Tested wet.		2		44	82	18
3	1 hour at 180° F. Tested at 180° F.				28	94	6
4	Continuous exposure to 97 percent relative humidity at 80° F.	1			70	69	31
		2			85	54	46
		4			78	58	42
		8			88	39	61
		12			69	60	40
		16			88	46	54
5	1 cycle (4 weeks): 2 weeks at 80° F. and 97 percent relative humidity, and 2 weeks at 80° F. and 30 percent relative humidity. Then repeated.	4		1	91	49	51
		8		2	74	59	41
		12		3	71	63	37
		16		4	95	31	69
		24		6	80	34	66
6	1 cycle (2 days): 1 hour in water at 122° F., 3 hours in wet steam at 200° F., 20 hours at 10° F., 3 hours at 212° F., 3 hours in wet steam at 200° F., and 18 hours in dry air at 212° F. Then repeated.		2	1	49	79	21
			4	2	50	91	9
			6	3	66	77	23
			8	4	38	96	4
			10	5	41	86	14
			12	6	32	94	6
7	1 cycle (2 days): 24 hours at 158° F., and 24 hours at 40° F. Then repeated.		10	5	92	42	58
			20	10	82	33	67
			30	15	82	57	43
			40	20	83	30	70
8	1 cycle (2 weeks): 2 days in water, 12 days at 80° F. and 30 percent relative humidity Then repeated.	2		1	88	35	65
		4		2	63	59	41
		6		3	80	52	48
		8		4	83	28	72
		12		6	50	53	47

[1]Each value is the average of 10 specimens from each panel subjected to exposures 1, 2, or 3, and of 5 specimens for each panel tested at the end of each period after being subjected to exposures 4, 5, 6, 7, or 8. The wall panels consisted of 0.020-inch aluminum faces bonded to a 2-inch-thick honeycomb core of resin-treated paper.

[2]Average of 4 panels.

Table 5.--Average properties of some sandwich facing materials[1]

Material	Thickness	Dry weight	Moisture content: Dry	Moisture content: Soaked[2]	Absorption[3]	Linear expansion[4]: Parallel to length of sheet	Linear expansion[4]: Perpendicular to length of sheet	Compression[5]: Maximum crushing strength	Compression[5]: Modulus of elasticity	Tension: Maximum tensile strength: Dry	Tension: Maximum tensile strength: Soaked[2]	Tension: Modulus of elasticity: Dry	Tension: Modulus of elasticity: Soaked[2]	Impact puncture resistance[6]: Dry	Impact puncture resistance[6]: Soaked[2]
	Inch	P.s.f.	Pct.	Pct.	Pct.	Pct.	Pct.	P.s.i.	1,000 p.s.i.	P.s.i.	P.s.i.	1,000 p.s.i.	1,000 p.s.i.	In.-lb.	In.-lb.
Douglas-fir plywood	1/4	0.74	8.0	69.4	28.0	0.10	0.22	5,170	1,280	6,060	4,950	....	959	581	568
Untreated hardboard	1/8	.75	4.8	36.5	11.0	.38	.37	3,420	672	3,460	1,800	669	308	198	212
do.	1/4	1.40	5.8	37.5	11.3	.23	.27	2,900	700	2,350	1,000	....	224	529	580
Treated hardboard	1/8	.77	5.7	30.7	9.4	.30	.37	5,260	900	4,980	3,020	855	382	206	225
do.	1/4	1.44	5.5	20.7	3.6	.26	.25	4,620	810	4,260	2,700	....	422	439	527
Finish hardboard	1/8	.73	7.4	67.1	29.3	.32	.33	3,300	681	4,570	990	679	93	271	252
Laminated paperboard,															
waterproofed	1/4	.70	9.6	72.9	18.3	.24	1.12	780	313	1,840	250	293	67	231	136
do.	3/8	.96	9.7	40.1	9.3	.21	1.05	780	317	1,700	420	294	79	344	276
Cement-asbestos board	1/8	1.36	4.2	12.0	9.8	.08	.08	7,130	2,678	2,730	2,060	2,627	2,162	163	148
do.	1/4	2.46	4.4	....	....	....	....	6,290	2,369	2,440	....	2,312	....	720+	....

[1]Average of 6 specimens from 3 sheets of material from commercial stocks.

[2]Soaked 7 days.

[3]Soaked 24 hours.

[4]Conditioned at 30 percent and then at 97 percent relative humidity.

[5]Compression tests in the dry condition only.

[6]Puncture by a pyramidal steel tup with triangular base 2.45 inches on each side.

Effect of Temperature and Moisture Changes on Bowing

Sandwich panels have large surface areas that may change appreciably in dimensions with variations of temperature or moisture content. When used in exterior walls of buildings, the two facings are generally exposed to different conditions and thus assume different dimensions; the resultant unbalance causes bowing or cupping. Defects in materials or manufacture can cause warping or twisting. Tests have shown that the change in dimension of a sandwich panel with equal facings and exposed to the same condition on both sides is practically the same as that of a free facing. Table 5 gives linear-expansion values for a number of facings.

Heat Transfer

A variety of sandwich-panel joint types were tested at the Forest Products Laboratory for heat conductivity, from a temperature of 73° F. in still air on the warm (indoor) side to -10° F. with moving air on the cold (outdoor) side. The panels were 3 inches thick, with XN-type paper honeycomb cores and 1/4-inch plywood or 0.02-inch aluminum facing. Under these conditions, the plywood-faced panel and the surface at a joint with a plywood-fiberboard spline had surface temperatures of about 66° F. on the warm side. These surface temperatures would require a relative humidity of nearly 90 percent indoors to cause condensation of water vapor.

The aluminum-faced panel had surface tem-

Table 6.--Mechanical properties of several types of honeycomb cores

Designation	Type[1]	Weight of assembled core	Compressive strength[2]	Shear properties[3]: Shear strength	Shear properties[3]: Modulus of rigidity
		P.c.f.	P.s.i.	P.s.i.	1,000 p.s.i.
A	Paper, corrugated	1.64	30	28	....
B	do.	2.58	63	74	....
C	Paper, expanded	1.96	45	....	....
D	do.	1.76	95	97	10.3
E	do.	3.96	360	306	20.6
F	Glass cloth	3.46	286	165	11.9
G	Aluminum	3.05	234	152	29.1
H	do.	4.41	436	244	41.9

[1]Core A, XN type, 30-lb. paper, 5 pct. phenolic resin; Core B, XN type, 50-lb. paper, 15 pct. phenolic resin; Core C, 60-lb. paper, 10 pct. phenolic resin; Core D, 60-lb. paper, 20 pct. phenolic resin; Core E, 125-lb. paper, 35 pct. phenolic resin; Core F, 112-114 glass cloth, phenolic resin, 1/4-in. cells; Core G, 0.002-in. foil, 3/8-in. cells; Core H, 0.002-in. foil, 1/4-in. cells; all paper cores tested dry; shear in cores D to H inclusive, parallel to core ribbons.

[2]Compression perpendicular to facings of sandwich, core ends laterally supported.

[3]Cores A and B, shear in bending. Cores D, E, F, G, and H, shear between two steel plates.

perature of about 57° F. on the warm side, 36° F. on the warm side of a joint with continuous metal from outside to inside, and intermediate values for other joints designed so that the continuity of the metal was interrupted from cold side to warm side. With a facing temperature of 57° F., condensation would occur at an indoor relative humidity of 65 percent, and with a temperature of 36° F., at a relative humidity of 30 percent.

Condensation

If sandwich panels with expanded or corrugated paper cores are used for exterior walls or roofs in cold climates, temperatures of the indoor surfaces of the sandwich may drop low enough to cause objectionable condensation of water vapor from the interior air, unless cores with more efficient insulation are used. The problem is most acute with sandwiches having metal facings and heat-conductive cores, and at joints or around openings.

Impact Bending

Impact bending tests were made on prototypes of a plywood-faced wall panel, an aluminum-faced wall panel, a plywood-faced floor panel, and an aluminum-faced roof panel. Panels were supported near the ends. Impacts were from a 60-pound sandbag dropped on the center of the panel from increasing heights until failure occurred. Heights of drop at failure were 8 feet for the plywood-faced wall panel, 7 feet for the aluminum-faced wall panel, and exceeded 10 feet for the floor panel and 4 feet for the roof panel. There was no damage from the 3-foot drop on wall or roof panels, or from the 6-foot drop on the floor panel. These values had been suggested as performance requirements in this test.

Concentrated Loading

Concentrated loads of 50 to 200 pounds on an area 1 inch in diameter caused less deflection of the aluminum-faced panels than that under design load in static bending. Permanent denting of the 1/50-inch facings occurred at loads ranging from 190 to 290 pounds. Tests made with a falling 2-inch steel ball on specimens of similar panels caused dents 0.01 to 0.03 inch deep from drops of 4 inches. Dents of equal depth were more noticeable in smooth bright sheets of metal than in materials like fiberboard, with a dull finish or texture.

Compressive loads up to 500 p.l.f. (pounds per lineal foot) caused negligible deformation and no damage to plywood- and aluminum-faced panels 8 feet in length. Three aluminum-faced panels failed by buckling of a facing at loads of 2,300 to 3,100 p.l.f. An 8-foot panel faced with 1/4-inch plywood had developed a load of 19,000 pounds per foot of width at failure.

Edgewise Loading

Three aluminum-faced panels were tested under an edgewise racking load. There was no structural failure at twice the design load of 60 p.l.f. of width. Ultimate strengths were from 250 to 640 p.l.f. when the panels were fastened and restrained in a manner similar to that expected in service.

Bending

Bending tests were conducted by supporting panels on rollers near each end and slowly applying load at the quarter points (fig. 9) until failure occurred. Strength values of panels not retained in the existing unit are given in table 7. All panels tested exhibited original strength values that far exceeded the strength requirements. Wall panels had strengths of five to twelve times the design load of 20 p.s.f. The floor panel tested had a strength nearly ten times the design load of 40 p.s.f. The aluminum-faced roof panels, which had a design load of 15 p.s.f., were the only roof panels tested to failure. Their strength was more than three times the design load.

Stiffness

Stiffness tests were made by supporting the experimental panels on rollers near each end and applying load at the quarter points until the design load was achieved. Stiffness values of panels not retained in the existing unit are given in table 7. All panels except the aluminum-faced ones had deflections at design load less than 1/270 of the

Table 7.--Properties of sandwich panels eliminated from the experimental unit

Panel No.	Core type	Facing	Type adhesive and press	Year installed	Stiffness[1]						Strength				
					Before exposure		After exposure				Before[2] exposure	After exposure			
					Deflection	Deflection span ratio	Year tested	Total exposure	Deflection	Change		Year tested	Total exposure	96-inch span	Change
					In.			Yr.	In.	Pct.	P.s.f.		Yr.	P.s.f.	Pct.
3N1	Corrugated XN	1/4-inch Douglas-fir plywood	Acid-catalyzed phenolic glue; cold press	1947	0.115	1/835	1948	1	0.102	+11	263	1948	1	391	+48
3S1	do.	do.	do.	1947	.115	1/835	1948	1	.098	+15	263	1948	1	344	+31
3N2	do.	1/4-inch cement asbestos	do.	1948	.070	1/1370	1961	13	.041	+41	194	1961	13	135	-30
3S2	do.	1/4-inch, high-density hardboard	do.	1948	.214	1/450	1961	13	.181	+15	315	1961	13	247	-22
4N1	do.	1/4-inch Douglas-fir plywood	do.	1947	.112	1/855	1962	15	.113	-1	263	1962	15	331	+26
4S1	do.	do.	do.	1947	.127	1/755	1962	15	.113	+11	263	1962	15	297	+13
5N1	Corrugated XF	do.	do.	1947	.182	1/525	1968	21	.149	+18		1968	21	670	
5S1	do.	do.	do.	1947	.162	1/590	1968	21	.151	+7		1968	21	430	
8N1	do.	1/8-inch Douglas-fir veneer with overlay	do.	1947	.141	1/680	1948	1	.127	+10		1948	1	272	
8S1	do.	do.	do.	1947	.158	1/610	1948	1	.141	+11		1948	1	330	
9N1	Expanded	0.02-inch aluminum	Phenol vinyl; press not known	1947	.365	1/260	1955	8	.365	0	200	1955	8	129	-36
9S1	do.	do.	do.	1947	.358	1/270	1955	8	.361	-1	200	1955	8	148	-26
9N2	Corrugated PNL	1/8-inch, high-density hardboard, porcelainized steel	Phenol resorcinol; hot press	1955	.053	1/810					222				
9S2	do.	do.	do.	1955	.053	1/810					222				
			ROOF PANEL												
E	Corrugated XN ventilated	1/4-inch, 3-ply plywood	do.	1947	.376	1/383	1968	21	.367	+2		1968	21	94	
			FLOOR PANEL												
4	Corrugated XN	3/8-inch, 5-ply plywood	do.	1947	[3].297	1/485	1968	21	.247	+17	376	1968	21	314	-16

[1]Based on design load of 20 p.s.f. for walls, 25 p.s.f. for roof, and 40 p.s.f. for floor.

[2]Based on test to failure of duplicate panel.

[3]Average for the 4 floor panels.

span which was selected as the maximum acceptable. The aluminum-faced wall panels had deflections only slightly greater than 1/270 of the span. The aluminum-faced roof panels deflected an average of 1/131 of the span; however, they were designed for a load of only 15 p.s.f. but tested under the roof design load of 25 p.s.f. At load of 15 p.s.f., deflection averaged 1/263.

This research paper supersedes U.S. Forest Service Research Paper FPL 12, of the same title, issued by the Forest Products Laboratory in 1964.